ROBUST AND REGENERABLE CARBON NANOTUBE FIELD EMITTER ARRAYS WITH INTEGRAL GATES

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Abstract

We have grown multi-walled carbon nanotubes by chemical vapor deposition on two types of gated structures, one containing a silicon post, another having an open aperture. Threshold below 20V and emission current up to 1 mA at 40V (from 0.5 mm^2 area) have been measured. Highly stable emission with a notable lack of electrical arcing have been observed. Emission was enhanced by ambient water vapor and hydrogen and was unaffected by xenon. Operation in 10^{-4} Torr hydrogen regenerated emission many folds from emitters degraded from operation in oxygen. Electron energy distributions reveal a current saturation phenomenon at energies just below the Fermi level, suggesting a limit in electron transport at the emission site. A gate current to anode current ratio of 2.5%, the lowest of any nanotube field emitter arrays (FEAs), was measured for the open aperture configuration.

INTRODUCTION

Carbon nanotubes (cNT) satisfy many demanding requirements for field emission, including stability, long lifetime, low voltage, high current-carrying capacity and mechanical strength. A key factor to their stability as field emitters is the lack of a nonvolatile surface oxide. Surface dielectrics such as oxides on conventional metal and silicon emitters could be the main cause for FEA catastrophic destruction by trapping charge which could lead to arcing [1]. Their small diameters (2-50nm) and high aspect ratios enable the high electric field enhancement for low voltage operation, despite the relatively high work function (~5.0 eV for graphite), which affords them a high degree of chemical inertness. Gating of cNT emitters has been undertaken only within the last five years, using two general approaches of patterning cNT paste or CVD growth of cNTs inside gated structures. The use of chemical vapor deposition (CVD) allows the nanotubes to be grown in much smaller micro-gated structures, thereby enabling lower operating voltages, much higher cell packing densities and total current densities.

EXPERIMENTAL

A nanotube FEA cell of our Type I configuration consists of CVD grown nanotubes on top of a gated silicon post centered in a 2.5 micron diameter gate aperture (See fig.1 of ref. 3). The growth starts with sputter deposition of a catalyst over a silicon-on-post FEA (with blunt post tips) from MCNC[2] and its preferential removal from areas except the top region of the posts. The nanotubes are grown using hot filament-assisted[3] or DC plasma CVD using C_2H_4 or C_2H_2 with NH_3. In Type II emitter cell configuration, nanotubes were grown on the sidewall of an oxide spacer lining a gated open aperture[4] with a 1.5 micron diameter (See fig.2 of ref.4). The catalyst was removed from the top surface by glancing angle ion beam sputtering prior to nanotube growth. A single gated array consisted of up to many thousands of cells for Type I emitters and only up to 40 cells for Type II emitters. Emission measurements (current-voltage, current-time, energy distribution) were carried out under UHV conditions (base pressure 10^{-10} Torr).

RESULTS AND DISCUSSION

The absence of arcing is one of the most prominent properties we have observed for these nanotube emitters, which we believe is due to the lack of a surface dielectric. This represents a major advantage over the conventional FEAs. Nanotubes can burn out but neighboring cNTs can keep on working. We observed emission at much lower voltages than those for conventional Mo and Si tip FEAs with comparable gate aperture diameters. For example, we obtained 1 mA emission at 40 volts gate voltage from a 0.5 mm^2 area of a Type I emitter array consisting of 30,000 cells. Good emission stability with few percent short term noise has been observed.[3] However, Type I emitter arrays exhibit a significant fraction of total current in gate current (leakage and interception) due to unfavorably aligned nanotubes in the cell.

We anticipate improvement by fabrication optimization such as better catalyst placement and aligned growth.

Dosing Type I emitter with H_2O vapor increased the emission up to an order of magnitude. This enhancement effect is consistent with observations by Dean and Chalamala[5] and could be attributed to the H_2O -nanotube surface dipole, which reduced the effective work function.

The effect of operating the emitter array in Xe gas ambient is of interest for Hall effect and ion thrusters for small satellites. We operated an array of our FEAs at a pressure of 10^{-5} Torr (the pressure used in thrusters) at 33 V gate voltage in DC mode for 15 hours without degradation in emission. The main contributing factor was the low voltages enabled by nanotubes, resulting in low ion energies and negligible sputtering.

Operating the emitter arrays at temperatures up to 700C has resulted in significant enhancement in emission, likely due to thermal effects on the Schottky barrier at the nanotube-silicon interface. This effect suggests that these emitters could be used for high temperature electronics applications such as switching devices in engines.

Prominent features of measured electron energy distributions include current saturation at an energy just below the Fermi level and the lack of significant shift in the leading edges as the gate potential (or current) is changed, the latter suggesting no significant potential drop in the contact (hence a good contact). During field emission, the already very low density of states near the nanotube Fermi level could become deficient of electrons because of insufficient rates of charge transport to refill them. This condition could result in the observed emission current saturation.

Emission from Type II nanotube emitters contrasts from Type I in that the gate current is only 2.5% of the anode current, the lowest observed to date for microfabricated gated nanotube emitters. We believe a contributing factor is that nanotubes in this open aperture configuration are aligned with a large directional component toward the center of the cell. Low gate current is essential for applications requiring high emission currents to prevent gate damage from heating.

Both Type I and II emitters have produce emission enhancements up to 2 orders of magnitude by operating in 10^{-4} Torr H_2. A reduction in the slopes of Fowler-Nordheim plots suggests a reduction in the effective work function due to a H-C surface dipole. Emitters degraded from overnight operation in O_2 recovered emission 340-fold by operating in H_2. These data suggest that atomic hydrogen (created by electron impact from the emitted electrons) is responsible for the large enhancement and regeneration effect by (a) removal of oxygen-containing surface species (which may act as p-type dopants and/or increase the work function), b) formation of a surface dipole (reducing the work function), and c) n-type doping by atomic hydrogen.

CONCLUSION

Microgating carbon nanotubes has effectively exploited their superior natural properties and has manifested them in the many desirable properties required for field emission devices - lack of arcing, low voltage, high current density, and ruggedness, making nanotubes premier candidates as field emitters.

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